SEQUENCE AND EVENT STRATIGRAPHY OF SILURIAN STRATA OF THE CINCINNATI ARCH REGION: CORRELATIONS WITH NEW YORK-ONTARIO SUCCESSIONS

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BRETT, C. E. & RAY, D. C., 2005. Sequence and event stratigraphy of Silurian strata of the Cincinnati Arch Region: correlations with New York-Ontario successions. *Proceedings of the Royal Society of Victoria* 117(2): 175–198. ISSN 0035-9211.

The Lower Silurian (Llandovery-Wenlock) of the eastern Cincinnati Arch in south central Ohio and northern Kentucky, USA, has been restudied from the standpoint of sequence and event stratigraphy. Despite a multiplicity of local stratigraphic terms a relatively simple pattern emerges. The succession, which comprises a major portion of the Tutelo Supersequence, is bounded at the base by the Cherokee Unconformity. It is further divisible into a series of six third order composite sequences and component fourth order subsequences that are correlative with Silurian sequences S-I, S-II and S-IV to S-VII, previously recognized in the Appalachian Basin. As in western New York-Ontario, sequence S-III has been removed by erosion at a major regionally angular late Llandovery unconformity. Correlation is corroborated by biostratigraphy and distinct event beds, including a very widespread deformed horizon (probable seismite), faunal epiboles, reef horizons, and probable K-bentonites. Similar patterns in the Silurian of the Niagara Escarpment in southern Ontario and western New York indicate probable allocyclic (eustatic) control over sequence development. However, the relatively simple sequence patterns are locally modified by epeirogenic uplift and subsidence. In particular, major truncation below sequence S-IV and thinning of strata in higher sequences to the west in Ontario and in western Ohio indicate that the Findlay-Algonquin Arch system was a positive area (forebulge?) by later Llandovery time. Moreover, a second area of regional uplift developed to the southwest in the vicinity of north central Kentucky during Wenlock time, as indicated by thinning and erosional truncation of parts of sequences S-V and S-VI. Changing loci of local uplift, as well as widespread K-bentonites and a major seismite are indicative of renewed tectonism of the Salinic Orogeny during this time.

Keywords: Silurian, Cincinnati Arch, sequence stratigraphy, eustasy, tectonics

IN recent years outcrop-based stratigraphic studies in cratonic areas have undergone a paradigmatic shift from a primarily descriptive approach to a focus on understanding the architecture of sedimentary accumulations within a sequence stratigraphic context (Wilgus et al. 1988; Kidwell 1991; Holland 1993, 1998; Dennison & Ettensohn 1994; Brett 1995, 1998; Emery & Myers 1996; Witzke et al. 1996; Catuneanu 2002; Coe & Church 2004). This avenue of research has developed indirectly from seismic profiling of continental margin sediments and from the recognition of large, unconformity-bounded depositional wedges ("sequences") in these profiles. Originally, sequences were defined very broadly as large intervals of strata bounded by very major unconformities ("first-" or "second-order" cycles recording tens of millions of years; see Vail et al. 1977, 1991), such as the six classic "super sequences" of Sloss (1963). Seismic stratigraphers were able to refine correlations and demonstrate that these large-scale unconformity-bounded packages are subdivisible into smaller intervals representing approximately 0.5 to 3 million years, typically termed "third-order" sequences. Sequence stratigraphers also recognized distinctive phases of sequences ("systems tracts") as the product of sea-level oscillations translated in a biased way into the sedimentary record (Vail et al. 1977, 1991; Haq et al. 1987; Van Wagoner et al. 1988; Emery & Myers 1996). Subsequently, seismic stratigraphers working in the field recognized that third-order packages could frequently be subdivided into smaller scale, "fourth-", "fifth-", and even "sixth-" and higher order cycles.

The purpose of this contribution is to examine and discuss Silurian strata of the eastern Cincinnati Arch region in eastern North America (Figs. 1, 2) in the context of sequence stratigraphy. Research on the sequence stratigraphy of Silurian rocks in the

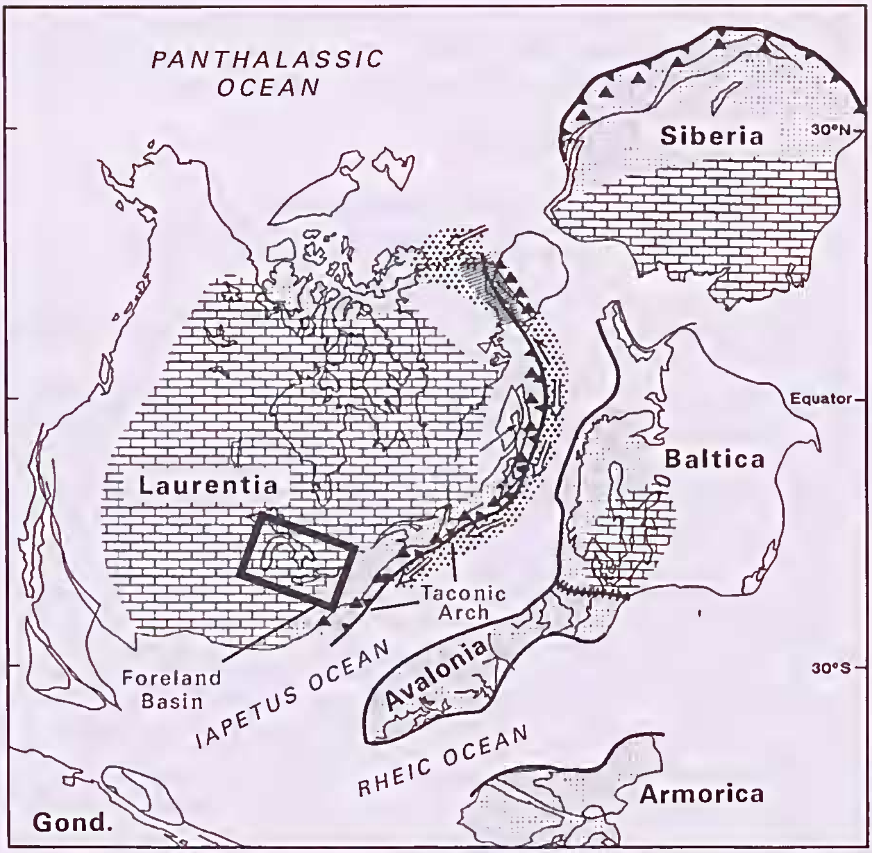

Fig 1. Paleogeographic reconstruction of Laurentia (ancestral North America) and adjacent paleocontinents during Early Silurian time. Note position of study area, shown with box and of the Taconic Arch and peripheral foreland basion. Gond.: Gondwana. Modified from Scotese (1990).

northern Appalachian Basin (Brett et al. 1990, 1994, 1998) has resulted in recognition of about eight widespread, unconformity-bounded packages that may be assigned "third-order" status, as well as a large number of smaller ("fourth-order") sequences. Recently, sequence analysis of correlative units in Ohio and Kentucky, USA, has led to recognition of about six, probably correlative "third-order" sequences in the Cincinnati Arch region (Fig. 2). Interregional correlation of these sequences is facilitated by the conodont biostratigraphic studies of Kleffner (1989) as well as the detailed subsurface study of Lukasik (1988).

We believe that the application of sequence analysis to this classic stratigraphic succession is providing critical new insights into the depositional dynamics and history of this region. In turn, these well-exposed strata may potentially help to refine models and approaches to stratigraphy that will aid in interpretation of other areas.

GEOLOGIC SETTING

Sediments of Early Silurian (Llandovery-Wenlock) age in southern Ohio and northern Kentucky accumulated in a shallow-marine subtropical setting about 20–25° south of the palaeoequator (Scotese 1990; Ettensohn 1992a,b; Figs. 1, 2). This setting was well situated to be affected by subtropical hurricanes and there is abundant evidence for storm deposition (tempestites) in the Silurian.

During the Late Ordovician, eastern Laurentia underwent collisions with island arc to microcontinental terranes, first (during the early Turinian or mid Caradoc Age) in the southern Appalachian region where collision produced the Blountian highlands and later (during the late Shermanian; late Caradoc) in the area of the New York Promontory where the Hamburg Klippe (SE Pennsylvania) and Taconic allochthons were emplaced as accretionary wedges onto the

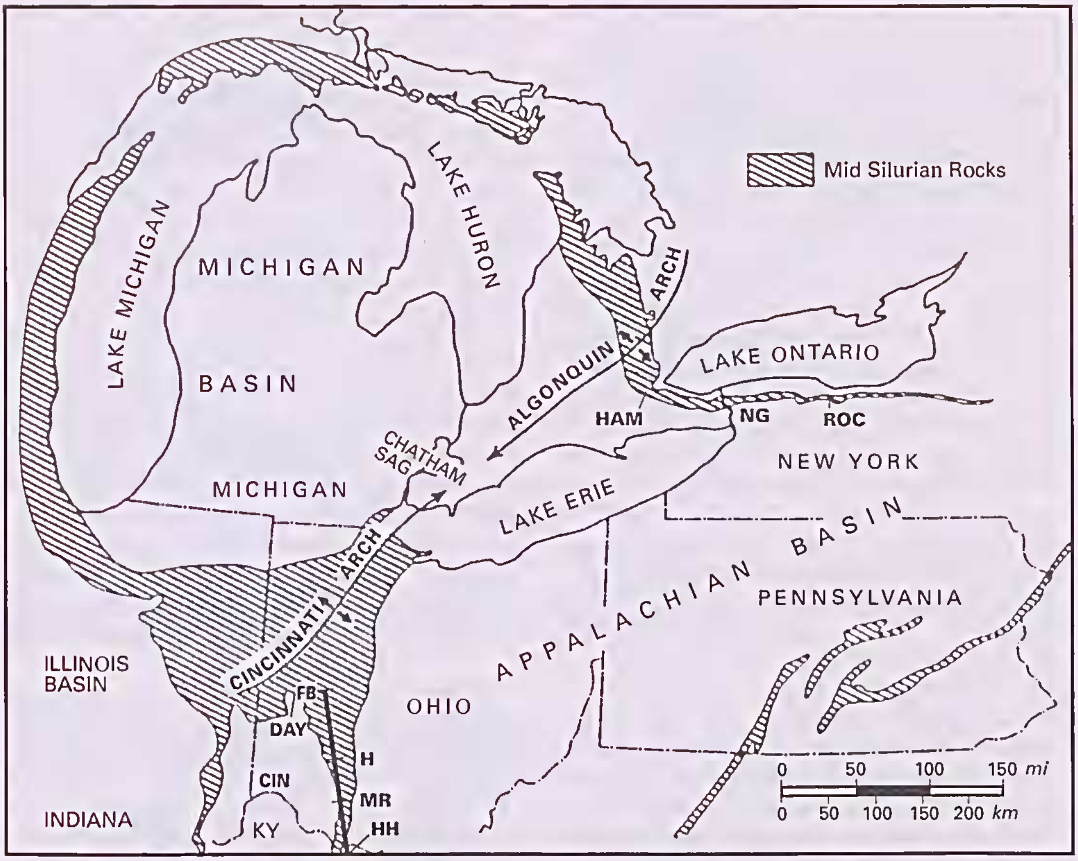

Fig 2. Map showing geomorphic features of eastern North America and outcrop belt of the Silurian; bar shows position of cross sections in Figures 6 (in part) and 14; abbreviations:DAY: Dayton, Ohio; CIN.: Cincinnati, Ohio; FB: Fairborn Quarry near Dayton, Ohio; HAM: Hamilton, ONT; H: roadcut on Rte. 62 at Hillsboro, Ohio; HH: Cut on AA Highway at Herron Hill, Kentucky; MR: cut on US Rte. 32 at Measley Ridge, near Peebles, Ohio; NG: Niagara Gorge, NY, ONT; ROCH: Rochester, NY. Base map modified from Telford (1978).

Laurentian margin forming the Taconian highlands (Ettensohn 1992c; Ettensohn & Pashin 1992; Fig. 1). Most of the siliciclastic muds and silts of the Upper Ordovician (Cincinnatian) and Lower Silurian were probably derived from these upland areas to the east and southeast. A relatively small gap existed between the two upland regions that might have served to funnel storms into the present-day Tristate region (Ohio-Kentucky-Indiana; Ettensohn 1992b, 2004).

The Taconic foreland basin (Fig. 1), a relatively narrow trough produced by thrust loading, extended southward from Quebec to Alabama (Beaumont et al. 1988; Ettensohn 1991; Ettensohn & Brett 2002). This area of active subsidence accumulated a thick wedge (up to 3900 m) of siliciclastic sands, silts and muds during the Late Ordovician- Early Silurian (Ettensohn 2004).

During the latest Ordovician to early Silurian, a major sea-level lowstand, probably related to continental glaciation in Gondwana (Brenchley et al. 1994; Brenchley 2004), caused the widespread withdrawal of seas from the Cincinnati area and created a major erosion surface, the Cherokee Unconformity (Figs. 3, 4). Evidence for local Llandovery glacial and interglacial events in South America (Grahn & Caputo 1992) suggests glacioeustatic control at least on Early Silurian cycles. Transgression in the Early Silurian (Rhuddanian) enabled deposition of marine siliciclastics and carbonates over the unconformity. This transgression spread a clastic wedge over much of the Appalachian Basin but clastic influx appears to have had rather little influence in the study area in which Brassfield carbonates were deposited contemporaneously (Gordon & Ettensohn 1984).

The Early Silurian interval is typically considered to have been tectonically quiescent. However, recent study (Ettensohn & Brett 2002; Ettensohn 2004; Fig. 3) indicates that a late tectophase of the Taconic Orogeny may have taken place at this time. Furthermore, a cluster of Early Silurian K-bentonites in the southern Appalachians indicates ongoing volcanism during this time (Huff et al. 1997). There is also some evidence for renewed tectonism, which produced renewed subsidence and a pulse of siliciclastics into the Appalachian basin during medial Silurian (latest Llandovery) time (Ettensohn 2004). In addition, recently discovered K-bentonites provide evidence for increased volcanism during late Llandovery-mid Wenlock time (Huff et al. 1997; Ray & Brett 2001; Brett & Ray 2001). Locally, evidence for renewed tectonism is provided not only by thick shales and siltstones of the Crab Orchard-Estill formations, but also by development of regional angular unconformities (Lukasik 1988; Goodman & Brett 1994; Ettensohn & Brett 1998; Figs. 3, 4). Regional truncation of Lower Silurian units in central Ohio and northward into the Hamilton, Ontario, area suggests that the Findlay-Algonquin Arch, the northeastern branch of the Cincinnati Arch, was uplifted during late Llandovery time (Ettensohn & Pashin 1992). The affected area cuts obliquely across the position of the former Sebree Trough. This could be viewed as evidence of reactivation of older deep-seated structures related to basement faults, but it has also been interpreted as development of a forebulge related to thrust loading and subsidence in the adjacent Appalachian foreland basin. In a sense, this could be viewed as the origin of the Cincinnati Arch (Ettensohn & Pashin 1992), although, in fact, the area of uplift was offset from the center of the present structural arch. The new stratigraphic correlations presented here will ultimately be used to refine understanding of migrating arches (forebulges) and depocenters through the Silurian.

GENERAL STRATIGRAPHY OF SILURIAN STRATA OF THE EASTERN CINCINNATI ARCH

Study Area and Methods

Recently, a series of detailed stratigraphic sections have been measured and correlated in southern Ohio into northern Kentucky along an approximately northwest-southeast line totaling about 170 km from the northern to the western flank of the present Cincinnati Arch, a broad, gentle antiformal feature that occupies portions of Ohio, Indiana, and Kentucky (Figs. 2, 4; Ettensohn & Pashin 1992). Measured sections span from Ludlow Corners, northwest of Dayton, Ohio southeastward through Highland and Adams counties, and across the Ohio River to cuts along the AA Highway near Vanceburg, Kentucky. Although this cross section takes in areas of disparate stratigraphic nomenclature, correlation of units appears relatively straightforward, at least when regional truncation of beds at unconformities is taken into account. Previous correlations were complicated by misidentification of the Estill (Crab Orchard) Shale with the somewhat younger, and lithologically distinctive Rochester Shale of New York and Ontario (cf. Potter et al. 1991). Also, the Laurel Formation of Indiana was incorrectly correlated with a thin carbonate beneath the Massie Shale in the Dayton area rather than with the Euphemia-lower Lilly formations (see Figures 12, 14, herein). Finally, while previous workers recognized an important unconformity

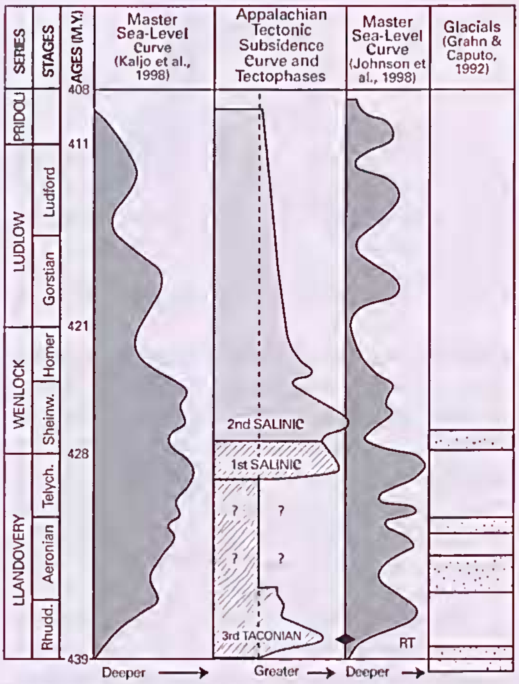

Fig 3. Silurian eustatic and tectonic events; note two slightly differing sea-level curves; tectophases include an early Llandovery pulse of the Taconic Orogeny and at least two tectophases of the Silurian Salinic Orogeny; also shown are documented ages of glacial deposits in South America. Modified from Ettensohn and Brett (1998).

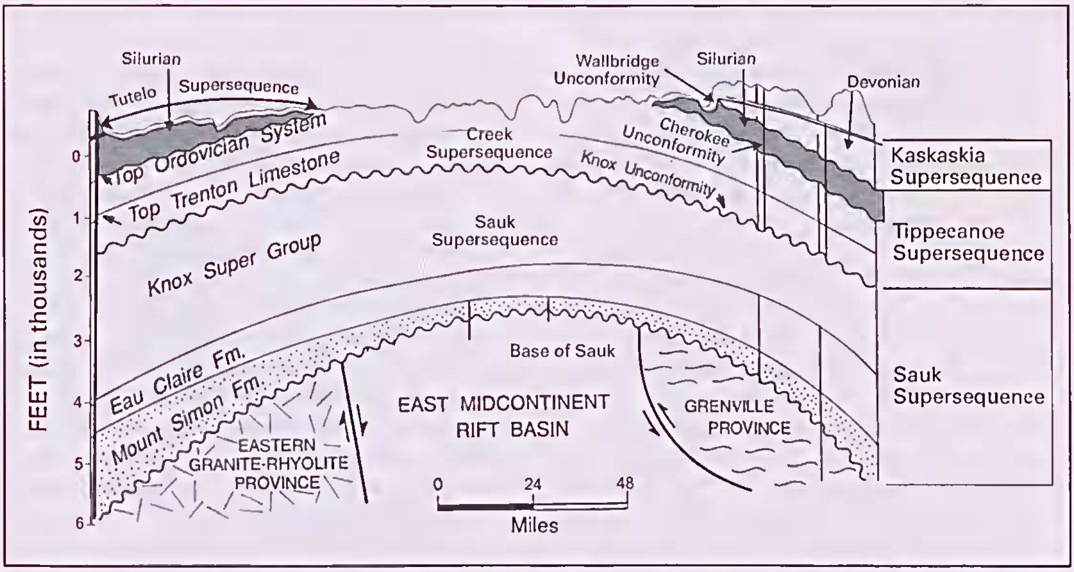

Fig 4. Schematic cross section of the Cincinnati arch region of southern Ohio/northern Kentucky, showing unconformities (supersequence boundaries) and Sloss sequences in the Ordovician. Note truncation of Silurian in center of arch. Adapted from Potter (1996).

beneath the Dayton Formation (Foerste 1906, 1935; Lukasik 1988), they failed to identify key sequence bounding truncation surfaces within the Bisher Formation and at the base of the Lilly Dolostone. Once these truncation surfaces were recognized the regional stratigraphic pattern was clarified and new patterns of paleogeography became evident.

Initially, we suspected that the Dayton-Vanceburg cross section would provide details of expansion of strata from the Algonquin Arch into the Appalachian foreland. However, it became clear that, while some Lower Silurian units (e.g., Estill Shale) showed a general southeastward expansion in thickness, upper units displayed a more complex pattern. In particular, the Massie (=Rochester) Shale thins both to the northwest and to the southeast of a maximum in Highland Co., Ohio. These observations suggest that the Findlay-Algonquin Arch was active during the middle to late Llandovery. A secondary arch developed later during the medial Silurian, in the vicinity of the later Waverly Arch in northern Kentucky.

Supersequences

At the largest scale, the rocks of the Cincinnati Arch-Appalachian Basin region are subdivisible into great unconformity-bounded packages of the scale recognized long ago by Sloss (1963). These large-scale "supersequences" are bounded by major unconformities that are traceable widely over the North American craton and perhaps globally (Dennison & Ettensohn 1994; Figs. 3, 4).

At their top, the Upper Ordovician rocks are bounded by a second great unconformity, the Cherokee Unconformity (Dennison & Head 1975). This unconformity is of global extent but of shorter duration (3–4 million years) than the Knox Unconformity, at the base of the Middle Ordovician Creek Supersequencee, having removed only the uppermost Ordovician Gamachian Stage over most of North America (Fig. 4). The Cherokee Unconformity is typically attributed to a major lowstand or drop in global sea level, probably of glacio-eustatic origin and related to coeval continental glaciation in North Africa (Brenchley et al. 1994; Brenchley 2004). This unconformity is typically nearly planar in outcrop but may display minor relief. In southern Ohio and northern Kentucky, the unconformity is in places very sharply delineated at the top of Upper Ordovician shales of the Drakes Formation, a greenish to red mottled mudstone with abundant thin siltstone layers that appears to represent the distal feather edge of the Queenston clastic wedge (Fig. 5). These variegated mudstones are sharply overlain by the Early Silurian (Rhuddanian) Brassfield Dolostone (Gordon & Ettensohn 1984). Although the Cherokee Unconformity is typically nearly flat and featureless, it clearly truncates different units in various localities and is a regionally angular beveled surface.

The Silurian strata are typically assigned to the Tutelo Supersequence (formerly combined with Creek as the Tippecanoe Megasequence of Sloss 1963; Fig. 4). The top of the Silurian in eastern Kentucky and southern Ohio is defined by a second major "second-order" sequence boundary comprising actually a combination of two or more unconformities. The lower, or Wallbridge Unconformity, separates upper Lower to Middle Devonian (Emsian-Eifelian) deposits of the Kaskaskia Supersequence (Sloss 1963; Dennison & Head 1975) from Upper Silurian to Lower Devonian deposits. In most areas of the Midcontinent, a higher Taghanic unconformity that occurred during a late Middle Devonian sea-level drawdown oversteps the Wallbridge Unconformity, and Middle Devonian deposits are absent. Both unconformities appear to record a combination of tectonic and eustatic signatures in their formation (Ettensohn 2004).

SEQUENCE STRATIGRAPHY OF SILURIAN STRATA OF CINCINNATI ARCH REGION

Cratonic Third OrderSequence Stratigraphy: General Concepts

Decameter-scale unconformity-bounded depositional sequences are present within the Silurian strata of the Cincinnati Arch region (Fig. 6). These are comparable in duration (1 to 5 million years) to the "third-order" sequences recognized by seismic stratigraphers (see for example Vail et al. 1991). In particular, they are subdivisible into smaller-scale sequences, parasequences, and systems tracts. Before discussing these stratigraphic packages in detail, the basic concepts of sequence stratigraphy will be reviewed briefly (see Catuneanu 2002; Coe & Church 2003 and, for recent summaries).

Sequences are relatively conformable packages of strata bounded by unconformities formed during sea-level lowstands. It has been recognized for some time that larger scale sequences typically are over generalized and that most such sequences are in fact composite sequences (Myers & Milton 1996). Such composite sequences can be subdivided into smaller scale cyclic intervals. Some of these are unconformity-bounded units that exhibit a pattern of relative deepening followed by shallowing (sub-sequences of Brett et al. 1990), whereas others are distinctly asymmetrical units that mainly record shallowing (parasequences of Vail et al. 1991).

Based partly upon the stacking patterns of parasequences, or architecture, of portions of sedimentary sequences, stratigraphers have been able to recognize distinct groupings of facies within sequences, referred to as systems tracts. Briefly, these include lowstand (LST), transgressive (TST), highstand (HST), and falling stage (FSST, or regressive) systems tracts. The lowstand systems tract (LST) is

Fig 5. Cherokee Unconformity (shown with arrows) between Upper Ordovician (Richmondian; Ashgill Stage) shales and overlying Lower Silurian (Llandovery; Rhuddanian) beds. A) Preachersville Shale Mbr. (Pr) of the Drakes Formation, sharply overlain by Belfast Member of Brassfield Formation (BB), lower massive cherty unit (BC); cut along KY Rte. 10, just west of Cabin Creek, Tollesboro, Lewis Co., KY. B) Queenston Shale (redbeds; Q) sharply overlain by white Whirlpool Sandstone (W); sharp flooding surface separates sandstone from overlying dark grey Power Glen (Cabot Head) Shale (PG), in turn sharply overlain by upper Medina Group (UM) reddish sandstones; West Jackson Street, Lockport, Niagara Co., NY.

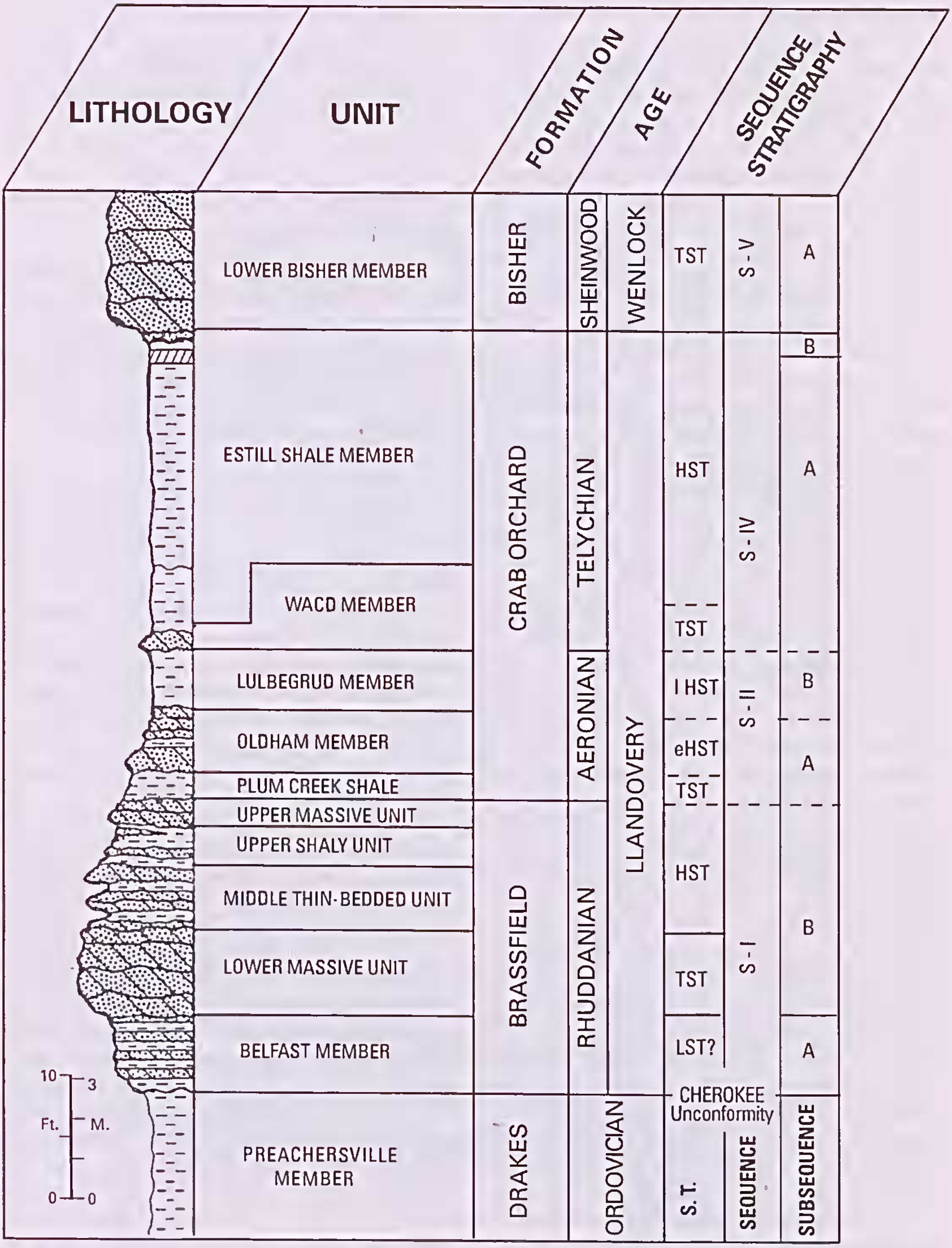

Fig 6. Generalized stratigraphic column and sequence stratigraphic interpretation for Lower Silurian (Llandovery) units in central Kentucky and south-central Ohio. Abbreviations: S.T.: systems tracts; LST: lowstand systems tract; TST: transgressive systems tract; eHST; early highstand systems tract; lHST late highstand systems tract. Note that each major (third-order) sequence is divisible into sub-sequences (sensu Brett et al., 1990), or fourth order sequences, labeled A and B. Stratigraphic profile adapted from Gordon & Ettensohn (1984).

defined as sediments that accumulate between true lowest actual fall of sea level and the beginnings of more rapid rates of sea level rise; these deposits include non-marine channel fillings that may occur locally immediately above a sequence boundary or erosion surface. In deeper water areas turbidite fans are another potential expression of lowstand accumulation during times when sediments are flushed from shallow water areas into deeper water regions. However, in most shallow shelf and ramp settings there are no LST deposits and the transgressive surface is superimposed upon the erosional sequence boundary (Myers & Milton 1996; Catuneanu 2002).

The transgressive systems tract (TST) may show a sharp transgressive erosion surface at its base, referred to as a ravinement surface. This transgressive surface reflects relatively rapid onlap of marine waters over a broad area. In many cases, including most of the sequences discussed herein, the sequence boundary and transgressive surfaces are combined into a single erosion surface, the ET surface (Myers & Milton 1996). The transgressive systems tract (TST) itself shows a deepening upward, retrogradational stacking pattern of smaller scale cycles or parasequences, and is bounded at its top by a surface of maximum flooding. This surface, which may be very distinct in some sequences, represents a time of minimal sedimentation in offshore marine settings associated with rapid sea-level rise, drowning of coastlines, and sequestering of siliciclastic sediments in nearshore estuarine and lagoonal depositional settings. Maximum flooding surfaces in the Silurian of eastern North America are typically marked by distinct but thin lag accumulations, phosphatic nodules, oolitic ironstones, or corroded shells and conodont enrichments (Brett et al. 1998). Immediately underlying and overlying the maximum flooding surface is a thin, time-rich section referred to as a condensed section that represents strongly sediment-starved conditions at times of maximum deepening.

The highstand systems (HST) tract typically commences with deeper water deposits, such as dark shales, that sharply overlie the maximum flooding surface. The highstand systems tract reflects sedimentation during the late portion of sea level rise; HSTs may show a progradational succession of smaller parasequences, i.e., an overall shallowing-upward pattern. In many instances, the HST can be differentiated from a falling stage (FSST) or regressive phase, in which progradational stacking of parasequences reflects an abrupt overall upward-shallowing (Catuneaunu 2003). Typically a sharp forced regression surface demarcates the base of the FSST, and, in some cases, a thin condensed lag bed may occur at this boundary (Brett 1995). The falling stage systems tract exhibits an overall shallowing and may be truncated at its top by the next major sequence boundary.

Description of Silurian Third Order Depositional Sequences

In the following sections the general sequence stratigraphy of the Lower Silurian in Ohio and Kentucky is described in ascending order and compared with reference sections in the north-central Appalachian Basin (Figs. 6, 7). The final section of this paper discusses the implications of revised stratigraphy for paleogeography, eustatic sea-level, and regional tectonics.

Sequence S-I. The first Silurian sequence (S-I) is the Medina or Tuscarora sandstone succession of the Appalachian Basin, which is recorded by the Lower Silurian (lower Llandovery) Brassfield Formation in Ohio and Kentucky (Figs. 5–7). It is bounded at its base by the Cherokee Unconformity (Fig. 5) and at its top by a more subtle and previously unrecognized sequence boundary marked by hematitic-phosphatic beds near the top of the Brassfield (Fig. 8). The equivalent sequence in western New York and Ontario consists of the Medina Group, comprising grey to reddish shales and sandstones (Brett et al. 1998; Fig. 7).

In the Cincinnati Arch region, the S-I basal unit is the Belfast Member of the Brassfield Formation (Fig. 8), an argillaceous dolostone and dolomitic shale that may resemble the underlying Drakes dolomitic shales. This interval apparently represents lowstand or initial transgressive conditions (Ettensohn 1992d). The basal bed of the Belfast Member is a massive, heavily bioturbated dolowackestone, 0.5 to 1 m thick; immediately above the sequence boundary the Belfast locally features a phosphatic, glauconitic lag. In central Kentucky this bed is a massive slightly glauconitic dolostone with spar filled burrow galleries near its top. The basal bed is sparsely fossiliferous, but contains scattered rugose corals and poorly preserved brachiopods. Locally it passes upward into a thin (0–0.5 m) interval of thin-bedded argillaceous dolostones and shales. The Belfast has been correlated with the Edgewood and Kankakee formations and, as with these units, is assigned an early Llandovery (Rhuddanian; sub-*Icriodina* Zone) age (Rexroad 1970; Berry & Boucot 1970). This

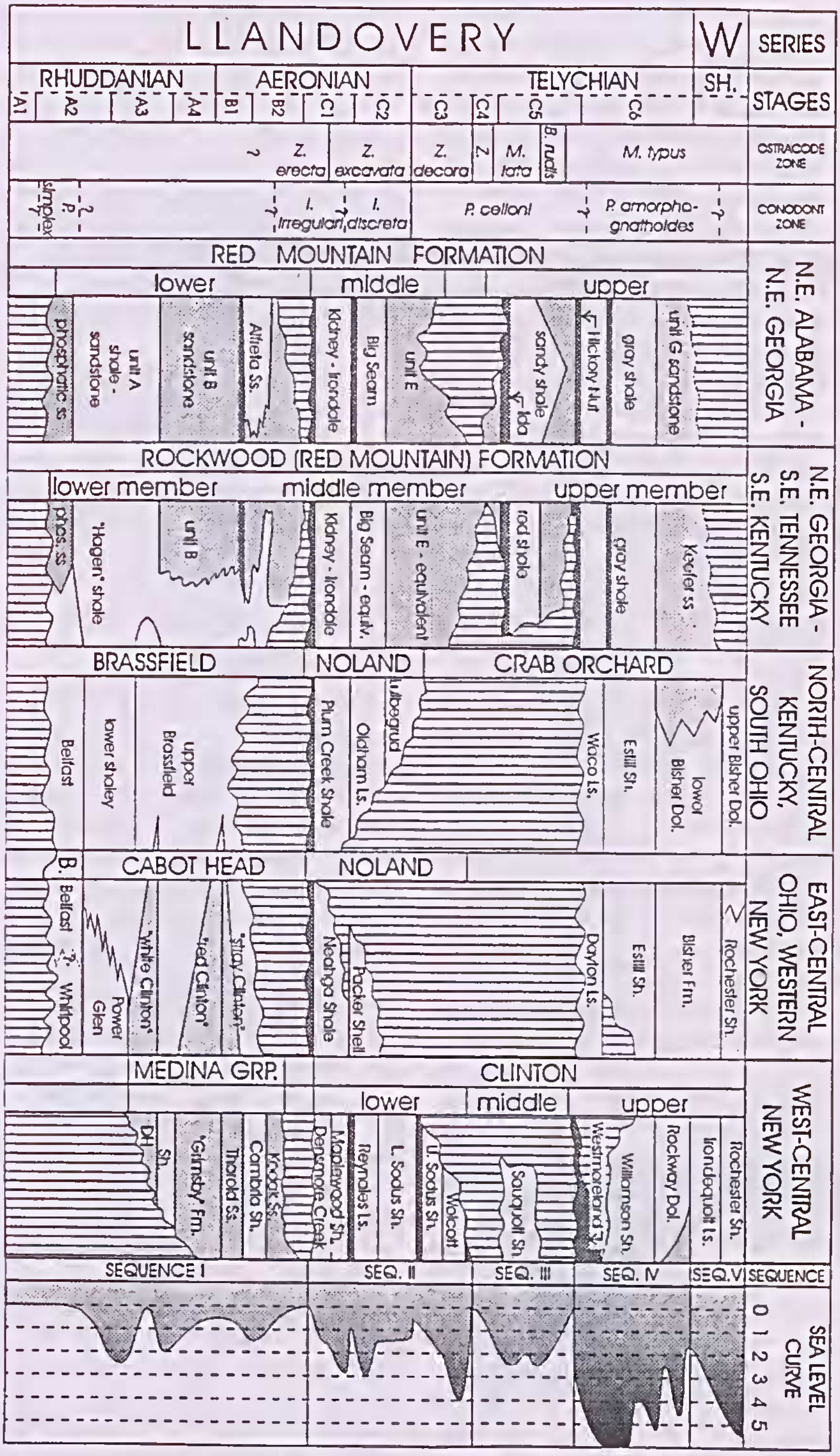

Fig 7. Correlation of Lower Silurian sequences in eastern USA; note particularly the comparisons of Kentucky, Ohio, and New York State. Curve on right side of diagram shows relative sea level curve for central New York State calibrated to benthic assemblages (BA-: shoreline, BA-2 above wave base; BA-3: average storm wavebase; BA-4 deep storm wavebase; see Brett et al. (1993) for discussion of depths of these assemblages. From Brett et al. (1998).

interval, together with the basal glauconitic bed, appears to form a transgressive-highstand couplet of a distinct minor (fourth-order) sequence, perhaps equivalent to the Whirlpool Sandstone in New York and Ontario (Fig. 5B). However, at the third-order scale this interval is interpreted to represent lowstand deposits of composite sequence S-I.

The next interval of the Brassfield Formation, (lower massive unit of Gordon & Ettensohn (1984) is a massive 1.5–3 m, orange buff-weathering crinoidal dolostone, typically with layers of light grey chert. The basal contact of the massive unit is sharp, and locally truncates some or all of the Belfast Member (Gordon & Ettensohn 1984; Fig. 8). This unit contains some fossils in common with the Manitoulin Formation of Ontario, its probable lateral equivalent. Both the Manitoulin and the bulk of the Brassfield Formation have been assigned to the Rhuddanian on the basis of conodonts of the *Icriodina irregularis* Zone (Rexroad 1970) and, in Ohio, brachiopods of the *Platymerella* Zone (Berry & Boucot 1970). Like the Manitoulin, the cherty Brassfield is interpreted as the upper portion of the TST of sequence S-I. The remainder of the Brassfield in southern Ohio and Kentucky consists of 8–10 m of thin-bedded, rippled dolostones that pass upward, into greenish grey shale and dolomitic siltstones, interpreted as tempestites (middle thin-bedded and upper shaly units of Gordon and Ettensohn 1984; Ettensohn 1992d; Fig.8). This interval probably constitutes the HST of sequence S-I and corresponds to the Cabot Head Formation of northern Ohio, Michigan and Ontario. Locally, near Dayton, the lower portion of this succession contains moderate sized bioherms or mud mounds with abundant pelmatozoan holdfasts, bryozoans, corals, and stromatoporoids

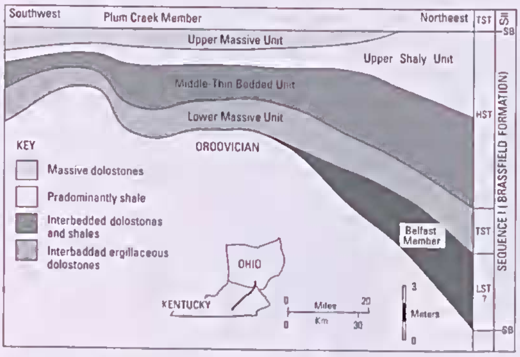

Fig 8. Regional cross-section of the Brassfield Formation in southern Ohio and northern Kentucky, showing distribution of sub-units. Sequence stratigraphic abbreviations as in Fig. 6. Adapted from Gordon and Ettensohn (1984).

(Lebold 2001; Schnieder & Ausich 2002). This occurrence indicates the buildup of bioherms during clean water conditions and rising sea level.

Sequence S-II. The second major Silurian sequence (S-II) is represented by a thin, poorly exposed succession assigned to the Noland or Crab Orchard formations (or groups) in southern Ohio and northern Kentucky, respectively (Figs. 6, 7). It corresponds to the lower part of the Clinton Group, mixed shales, carbonates and ironstones, in the Appalachian Basin (Figs. 7, 9).

The base of this sequence is represented by a dolostone unit that is capped by a hematitic bed rich in large discoidal pelmatozoan columnals, the so-called "Bead Bed" (Foerste 1935) or upper massive unit of the Brassfield (Gordon & Ettensohn 1984; Ettensohn 1992d; Fig. 8); this unit locally contains an abundance of the brachiopod *Cryptothyrella subquadrata* (formerly *Whitfieldella subquadrata*) and was mapped widely, as the "*Whitfieldella*" bed in central Kentucky by Foerste (1906). Most authors have included the "Bead Bed" as an uppermost unit in the Brassfield, but Gordon & Ettensohn (1984) recognized that it represents part of a distinct sequence. The base of this bed is sharply set off from the underlying shales of the uppermost Brassfield succession and represents the sequence boundary. We interpret the Bead Bed as a transgressive systems tract; the abundance of hematite and phosphatic nodules at the top of the interval indicates prolonged sediment starvation associated with maximum rates of sea level rise. This bed has a counterpart in the early Llandovery Densmore Creek phosphatic bed and Webster bed phosphatic conglomerate in New York State (LoDuca & Brett 1994; Fig, 9).

The main Plum Creek Member of the Noland Formation in southern Ohio and central Kentucky consists of about 1–2 m of greenish grey, sparsely fossiliferous shale, dated as late Rhuddanian to early Aeronian age (Berry & Boucot 1970); we equate this unit with the Maplewood-Neahga shales of western New York (Figs. 7, 9) and to the lowest tongue of the Rose Hill Shale in Pennsylvania. As with those units, the Plum Creek is sparsely fossiliferous, but passes laterally into skeletal limestones and becomes indistinguishable from the Oldham Limestone in the area of Berea, Kentucky (Foerste 1906). This suggests that the Plum Creek may represent an "in-board" or lagoonal shale, as is the Maplewood, that passes westward into offshore shoal carbonates (see LoDuca & Brett 1994).

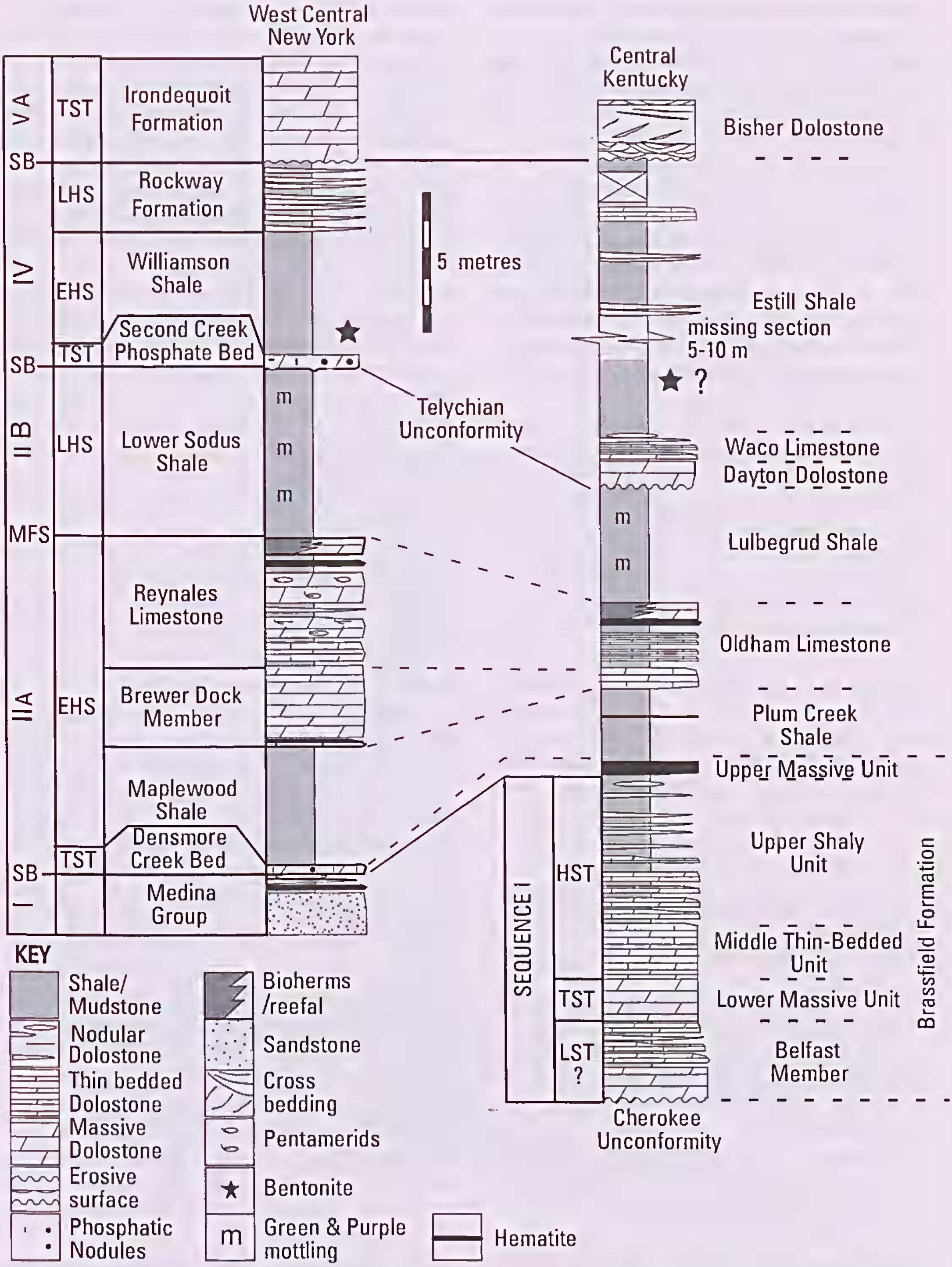

Fig 9. Comparison of Llandovery lithostratigraphic succession and inferred sequence stratigraphy in central New York State (vicinity of Rochester, NY) and central Kentucky/ southern Ohio. Sequence stratigraphic abbreviations as in Fig. 6.

Also included within sequence S-II in Ohio are the overlying Oldham Limestone and Lulbegrud Shale, which have been tentatively correlated with the Reynales Limestone and Sodus Shale of the classic New York section (Fig. 9; Lukasik 1988; Brett et al. 1990, 1998).

The Oldham Limestone comprises about 3–4 m of dolomitic wacke- and packstones, bearing a moderately diverse fauna. This limestone is dated as mid Llandovery Aeronian (C1–C2) age on the basis of conodonts (Kleffner 1990) and the brachiopod *Microcardinalia triplesiana* (formerly *Stricklandia triplesiana*; Berry & Boucot 1970). Ferruginous limestone below this bed may record a discontinuity, perhaps associated with the Sterling Station Iron Ore in the New York Clinton.

The Lulbegrud Shale is also about 3–4 m thick and comprises largely barren, greenish grey shale. This unit is poorly dated. Huddle (1967) reported *Neospathognathodus celloni* Zone conodonts from this unit suggesting a middle Telychian (C5) age, as in the Sodus Shale of New York (Fig.9). Together, the Oldham Limestone and Lulbegrud Shale may represent the TST and HST, respectively, of a small-scale (fourth order) sequence.

Sequence S-IV In Ohio the Lulbegrud Shale, Oldham Limestone, and Plum Creek Shale are successively truncated to the northwest and overstepped by the Dayton Dolostone, a distinctive, thin, highly bioturbated glauconitic carbonate (Lukasik 1988; Fig. 10). In central Kentucky the Dayton interval is represented by the compact, basal, 30–60 cm, dolomitic limestone bed of the Waco Limestone Member (Figs. 9,10). This bed is gradationally overlain by up to 2 m of thin bedded, highly fossiliferous limestone and shale near Irvine, Kentucky. Together, these beds of the Waco record a diverse and abundant fauna, especially rich in rugose and tabulate corals, including *Strombodes*, *Arachnophyllum*, *Chonophyllum*, and *Polyorophe*, some of which resemble those found in the late Llandovery of Ontario as well as in the Wenlock of England and Gotland (Foerste 1906).

The Dayton Dolostone has been dated as late Llandovery (mid-Telychian, N. celloni Zone) on the basis of conodonts (Kleffner 1990). The Dayton is thus approximately coeval with the Merritton Limestone and upper Fossil Hill Dolostone, which similarly overstep strata of sequence S-II in the Bruce Peninsula area of southern Ontario, Canada (Stott & Von Bitter 1999; Fig.7). Correlation of the Waco-Dayton with the upper Fossil Hill is further supported by similarities in the coral fauna. This interval may correlate with the Westmoreland Iron Ore and equivalent Second Creek Phosphate bed in New York (Lin & Brett 1989; Brett et al. 1990). The Dayton-Waco carbonates are, correspondingly, interpreted as the TST of sequence S-IV; with sequence S-III (Sauquoit Shale), as well as upper parts of Sequence S-II (Wolcott Limestone), removed beneath the basal unconformity, as in western New York and Ontario (Lin & Brett 1988; Brett et al. 1990).

Brett et al. (1990) inferred that the sub-Dayton unconformity of central Ohio and the sub-Merritton-Fossil Hill unconformity in Ontario are local manifestations of the same regional unconformity. It probably represents a minor episode of uplift and erosion along the Algonquin Arch, which was evidently active during the medial Silurian. Goodman & Brett (1994) suggested that this activity may reflect an isostatic response to thrust loading during early phases of the Salinic Orogeny (Fig. 3).

The HST of the fourth Silurian sequence (S-IV) is represented by the 10 to 20 m Estill Shale (a member of the Crab Orchard Formation in Kentucky terminology), which overlies the Dayton Limestone in the Dayton, Ohio region and the equivalent Waco Limestone in central Kentucky. (Figs.7, 9).

In southern Ohio and northeastern Kentucky the Dayton-Waco carbonates appear to be absent and a thick shale (perhaps as much as 45 m thick in West Union, Ohio; Foerste 1906), mapped as the "Estill Shale", may actually be equivalent to both the Estill (*sensu stricto*) and the underlying Lulbegrud Shale (Fig. 11). Lower and upper units are separated by a subtle but regionally angular unconformity. The "lower Estill Shale" consists of purplish shales and contains an ostracode and conodont fauna suggestive of a mid Telychian age; this could correlate with either the upper Sodus Shale (sequence S-II) or the Sauquoit Shale (sequence S-III) of the New York succession (Brett et al. 1990, 1998). At the roadcut on the AA Highway near Charters, Kentucky (Fig. 11), a subtle but slightly angular discordance appears between the lower purplish shales and the overlying greenish-grey shales and siltstones of the upper Estill Formation (Mason et al. 1992a). At most, a thin transgressive lag deposit occurs at the base of sequence S-IV.

The upper Estill Shale is assigned a latest Llandovery (late Telychian) age on the basis of graptolites of the *Monograptus cf. M. clintonensis* Zone and conodonts of the *Pterospathodus amor-*

phognathoides Zone (Rexroad 1970; Kleffner 1987). The lower five meter interval of shale and thin, fossiliferous siltstones appears to correlate directly with the uppermost Rose Hill Shale of the Appalachian Basin and with the Williamson- Willowvale shales (sequence S-IV) of the standard New York section (Fig. 9). This represents the highest stand of relative sea level during the Silurian in eastern North America and appears to reflect a global eustatic highstand (Johnson 1996; Johnson et al. 1998).

The uppermost Estill dolomitic siltstone unit (previously assigned to the overlying Bisher Formation; Potter et al. 1991; Mason et al. 1992a,b), which is regionally removed under the S-V unconformity at the base of the Bisher Dolostone, comprises thin- to medium-bedded dolomitic and somewhat fossiliferous carbonates, interpreted as tempestites (Aigner 1985; Mason et al. 1992a) and greenish-grey shales. This dolomitic siltstone appears to correlate directly with the Rockway Formation of Ontario and New York State and with the lower Keefer Sandstone or sandy uppermost Rose Hill Formation in Pennsylvania (late highstand of sequence S-IV; subsequence S-IVB; Figs. 6, 7, 9). To the northwest, near Dayton, Ohio, the Estill appears to grade into rhythmically bedded shale and dolomitic carbonate of the lower shale member of the Osgood Formation (Fig. 10).

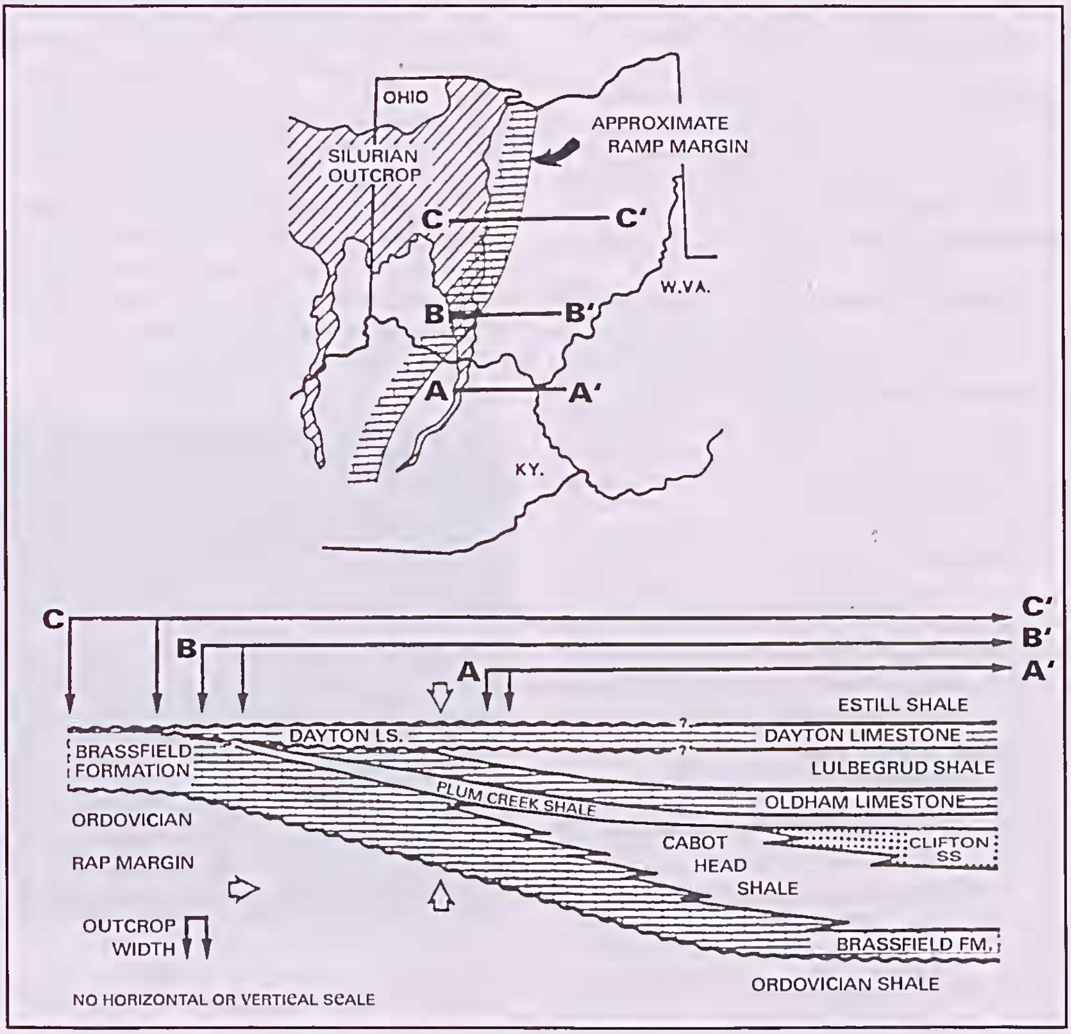

Fig 10. Regional cross sections of Silurian strata through south-central Ohio and northern Kentucky. Note the regional truncation of units along a proto-Findlay Arch (northwest or left side of cross section) below a major unconformity beneath the Dayton Limestone. Adapted from Lukasik (1988).

Also, probable K-bentonites have been found in this interval, which may correlate with beds in the Osgood Shale on western flank of the Cincinnati Arch (Ray & Brett 2001; Brett & Ray 2001). These ash beds may also correlate with K-bentonites found in the upper Llandovery of the southern Appalachians (Huff et al. 1997). Work on these beds is preliminary but appears promising. In particular a 1–3 cm greenish clay bed low in the Osgood Shale at Fairborn, Ohio appears to be traceable into outcrops of the Osgood in southern Indiana. It may also correspond to a bentonite reported from the upper Estill Shale at Charters, Kentucky (Mason et al. 1992a) and one or more thin yellowish weathering clay beds (probable K-bentonites) in the lower Williamson Shale at Rochester, NY (Brett et al. 1994).

Sequence S-V A very distinct sequence boundary at the base of the Bisher Dolostone separates overlying Sequence S-V from the underlying Estill Shale. At this surface, the uppermost Estill dolomitic siltstones and shales appear to be regionally truncated along a series of outcrops near Vanceburg, Kentucky (Figs. 7, 9, 12).

Sequence S-V shows a well-defined transgressive systems tract, recorded in crinoidal dolomitic packstones and grainstones, rich in the brachiopod *Whitfieldella oblata*, now assigned to the lower unit of the as-yet undifferentiated Bisher Formation (Figs. 12–15). This interval has yielded conodonts indicating a *Spathognathodus ranuliformis* Zone age (Rexroad 1970; Berry & Boucot 1970; Kleffner 1989, 1991); this bed is aligned with the similarly dated crinoidal grainstones of the Irondequoit Formation in western New York (Rexroad & Rickard 1965). The top of the lower Bisher unit is thus interpreted as a major flooding surface corresponding to the upper glauconitic condensed bed of the Irondequoit Limestone in western New York. This is sharply overlain by a thin shaly HST interval, termed Massie Shale in the Dayton, Ohio area, apparently correlative with the Rochester Shale in the Appalachian Basin (Figs. 12, 13). This interval also correlates with the thin upper shale unit of the Osgood Member in Indiana, which has yielded a fauna of brachiopods, bryozoans and echinoderms very similar to those of the Rochester Shale in New York (Frest et al. 1999). No more than a half-meter of shales and thin calcisiltites occurs at this level in Kentucky. However, to the north, near Hillsboro, Ohio, a succession of nearly three meters of typical Massie (="Rochester") Shale overlies the basal grainstones of the Bisher Dolostone. The succession thins again toward Dayton, Ohio (Figs.13, 14).

A very interesting laminated dolostone bed up to 1 m thick overlies the "Massie" shale interval. Locally, as near Peebles, Ohio, this bed shows strong ball-and-pillow style deformation. The interval very closely resembles the DeCew Dolostone, which sharply overlies the Rochester Shale in western New York and Ontario (Figs. 12, 15). In all of its outcrops the DeCew is similarly heavily deformed. We suggest that the contorted beds in the upper Bisher/Massie units and the DeCew Dolostone represent coeval, sandy, detrital carbonate facies associated with a forced regression; i.e., they represent the falling stage systems tract of sequence V, and their typically sharp base indicates a forced regression surface. Moreover, the occurrence of deformation in this interval over a vast region suggests that these beds record extremely large seismic shocks. Pope et al. (1997) and McLaughlin & Brett (2004) documented similar very widespread deformation in similar regressive detrital carbonates in the Ordovician of Kentucky. We suggest that these widespread deformed beds record not only appropriate ("deformation-prone") facies, but also a "trigger" provided by seismic shocks. Such seismites may provide very useful regional event stratigraphic markers (Pope et al., 1997; McLaughlin and Brett, 2004).

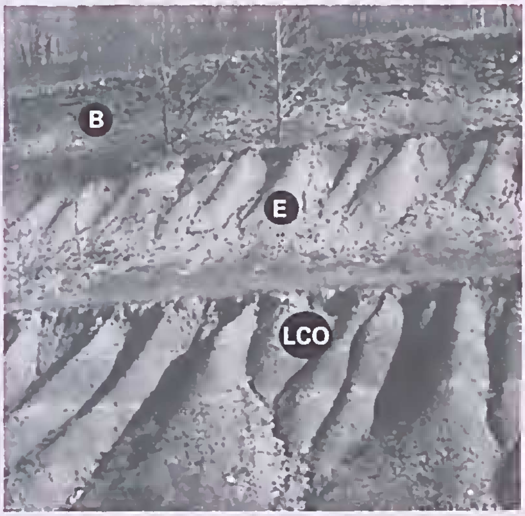

Fig 11. Roadcut section along AA Highway (KY Rte. 9/10) at Charters, Lewis Co., KY showing Crab Orchard Shale overlain by Bisher Dolostone (B), near top off view. Lower Crab Orchard beds are maroon shales with thin siltstones and possible K-bentonite showing apparent slight discordance with overlying lighter greenish grey (Estill) shale. Height of cut is approximately 25 m.

Sequence S-VI. The remainder of the Bisher Formation contains a complex facies mosaic, the details of which are somewhat obscured by dolomitization (Mason et al. 1992b). A cryptic, but important, sequence boundary occurs above the Massie calcisiltite and shale interval. This sequence boundary appears to correlate with the base of the Lockport Group and the base of the McKenzie

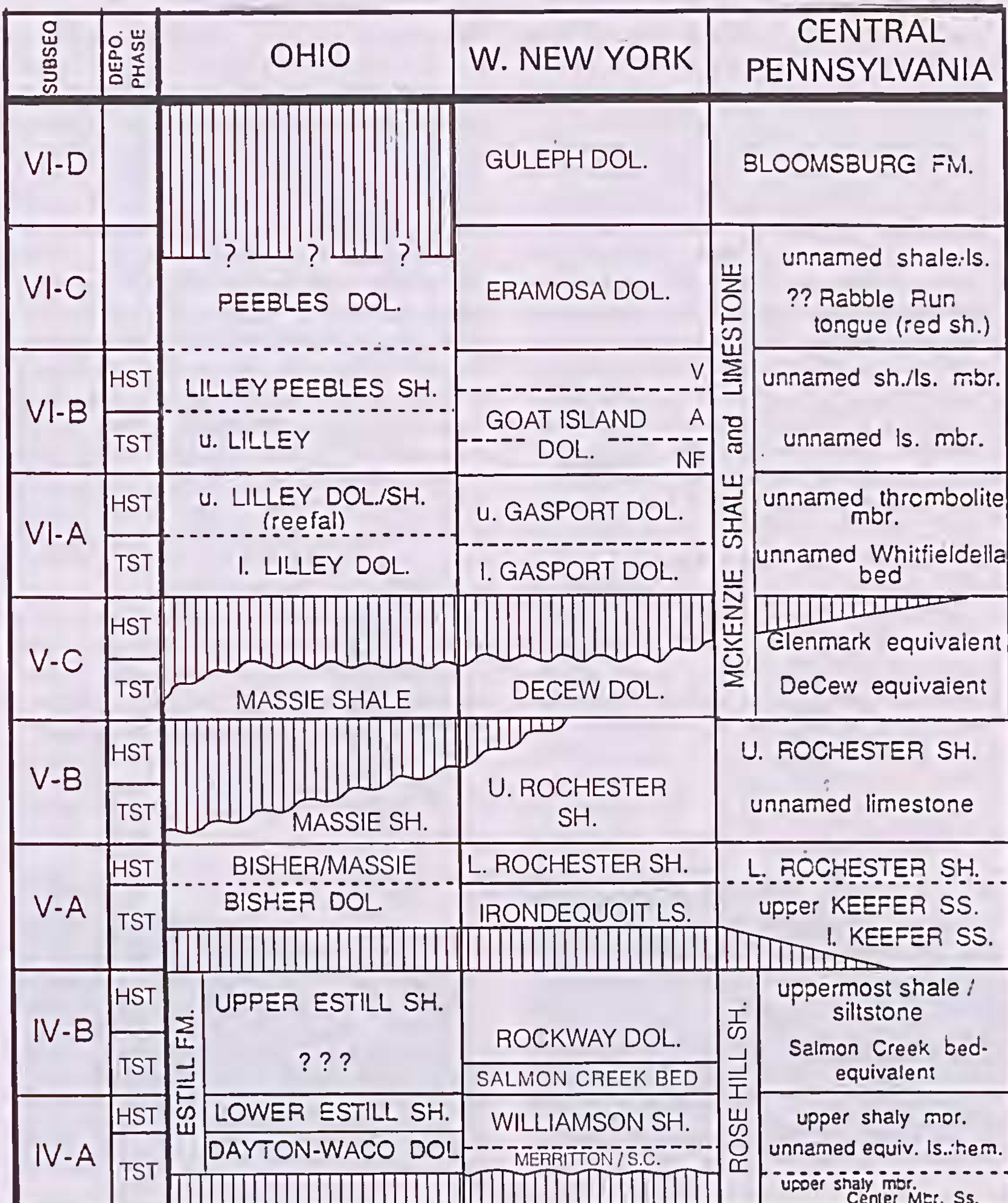

Fig 12. Summary of correlation of upper Llandovery-Wenlock units in central Ohio, New York State/Ontario, and Pennsylvania. Abbreviations for members of Goat Island Formation: NF: Niagara Falls (massive dolostone); A: Ancaster (cherty dolostone) Member; Member; V: Vinemount (shaly dolostone) Member; SC: Second Creek phosphate bed of Williamson shale; terminology of Brett et al. (1995).

Formation in Pennsylvania and Maryland and represents the base of sequence S-VI (Figs. 8, 12). This interval is represented by hummocky to herringbone cross-stratified, crinoidal dolostones, assigned to the upper Bisher Formation in Kentucky and to the Bisher or lower Lilly Formation in Adams County, Ohio (Figs. 14, 15; Ausich 1987; Kleffner & Ausich 1988; Kleffner 1990). Local abrupt changes in thickness and facies within this succession are typical (Mason et al. 1992a,b) and may represent the development of a series of skeletal megashoals and intershoal areas during this part of Wenlock time (Pratt & Miall 1993). The top of this succession contains a distinctive, poorly bedded interval that appears as a series of mounds or blocks of dolomicrite surrounded by poorly bedded dolomitic mudstones. This interval has been interpreted as a collapse breccia associated with karstification during the Devonian because it lies just below the Kaskaskia unconformity in several locations. However, close examination of the mounds revealed the presence of heavily dolomitized corals, stromatoporoids and crinoid holdfasts. Thus, we interpret the mounds as bioherms (Fig. 14). This interval thus appears to be a continuation of the Gasport biohermal interval, widely distributed in the Appalachian Basin in western New York and Ontario (Crowley 1973; Smosna & Patchen 1992; Fig. 15). At Hillsboro, Ohio it appears that this interval passes laterally into a greenish shaly dolostone and shale interval that we would correlate with the upper or Pekin Member of the Gasport Formation (Brett et al. 1990). Just why biohermal buildups are so prolific at this horizon is poorly understood but we suggest a combination of low siliciclastic sedimentation during an episode of gradual sea level rise (Crowley 1973; Smosna & Patchen 1992).

The overlying upper Lilly Dolostone succession of southern Ohio comprises massive crinoidal dolostone, locally with chert nodules; this interval appears to grade laterally to the northwest into the Cedarville Dolostone near Dayton, Ohio (Fig. 14). This interval has yielded conodonts of the *Ozarkodina saggita rhenana* Zone (Kleffner, 1990); it is lithologically similar to the correlative lower Goat Island Dolostone (Niagara Falls, and Ancaster cherty members of Brett et al. 1995) in western New York and Ontario. A shaly interval identified as the "Lilly-Peebles transition", in south-central Ohio (Ausich 1987; Kleffner and Ausich, 1988) records a distinct deepening event. We tentatively correlate this interval to shaly dolostone and shale of the Vinemount Member in Ontario and western New York (Brett et al. 1995), and possibly to the Waldron Shale of Indiana and Kentucky. A preponderance of shale during this interval throughout much of eastern North America, may suggest a deepening and influx of siliciclastics associated with the second tectophase of the Salinic Orogeny (Ettensohn & Brett 1998); alternatively it may record a widespread late Wenlock eustatic highstand (Johnson et al. 1998).

The Peebles Dolostone, the highest Silurian unit present in south-central Ohio, consists of massive vuggy dolostone that may relate to the Eramosa Dolostone of Ontario. The contact of this unit on the underlying shales is sharp, and probably represents the VII sequence boundary (Brett et al. 1995). However, the biostratigraphy of the Lilly-Peebles and Peebles interval requires further study to test these correlations.

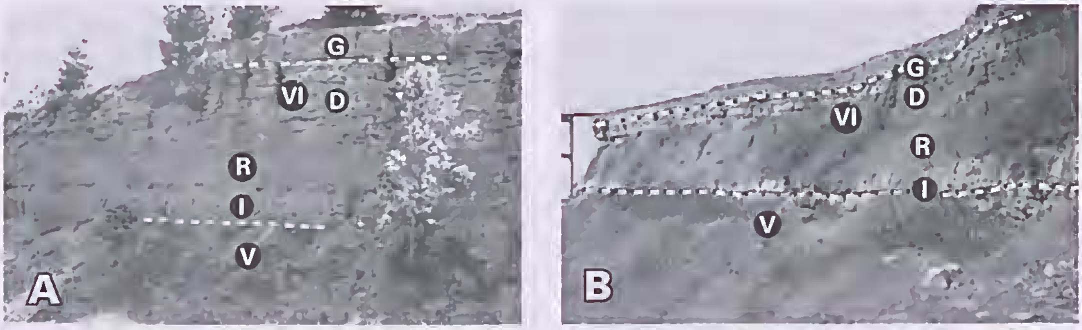

Fig 13. Comparative stratigraphy of sequences S-V and S-VI in Ohio and New York. A) section of upper Estill and Bisher formations;Rochester Shale equivalent R is about 3 m thick; roadcut along US Rte. 62 just south of Hillsboro, Highland Co., Ohio. Note comparable succession of units in Ohio correlative with those of western New York. B) Upper Clinton and Lockport Groups; Rochester Shale is approximately 20 m thick. Niagara Gorge near Lewiston, Niagara Co., NY. Symbols for New York units and their probable equivalents in Ohio include: I: Irondequoit Limestone; R: Rochester Shale; D: DeCew Dolostone; G: Gasport Limestone. Two sequence boundaries are present here marked V and VI (note arrows).

The upper Lilly to Peebles interval has been largely removed by Devonian erosion in northern Kentucky. Toward Dayton, however, higher Silurian units, as well as Middle Devonian beds emerge as this unconformity becomes less prominent. In the southeastern part of the study area grey to black pyritic shales of the Upper Devonian (Famennian) are juxtaposed directly upon eroded Silurian carbonates (see Fuentes et al. 2001). The unconformity typically displays a small amount of relief and may be overlain by a thin lag deposit of dark bone and conodont-rich pyritic to phosphatic limestone. Corrosion and some dissolution of the underlying Silurian carbonates is typical.

Figure 14 illustrates a northwest-southeast correlated cross section based upon four major outcrops at Fairborn, Ohio to Herron Hill, Kentucky; terminology follows Ausich (1987) and Kleffner & Ausich (1988). A similar succession of units is present over this region, although similarities have been masked by different terminology and offset of contacts: A) ("Laurel"-lower Bisher Fm.) a lower compact, massive crinoidal brachiopod-rich limestone/dolostone rests sharply on shales or shaly dolostones, and is overlain by B) (Massie Shale) soft, medium to dark grey shales and/or argillaceous dolostones, capped, in turn, by C) (part of Massie Shale) laminated to hummocky cross stratified dolomitic siltstone or silty-sandy dolostone typically with internal deformation. The latter is sharply overlain by D) (Euphemia, upper Bisher Fm.) massive, cross bedded, sandy crinoidal dolostone which grades upward into E) (Springfield-upper Bisher Fm.) thin bedded dolostones with dolomitic shale

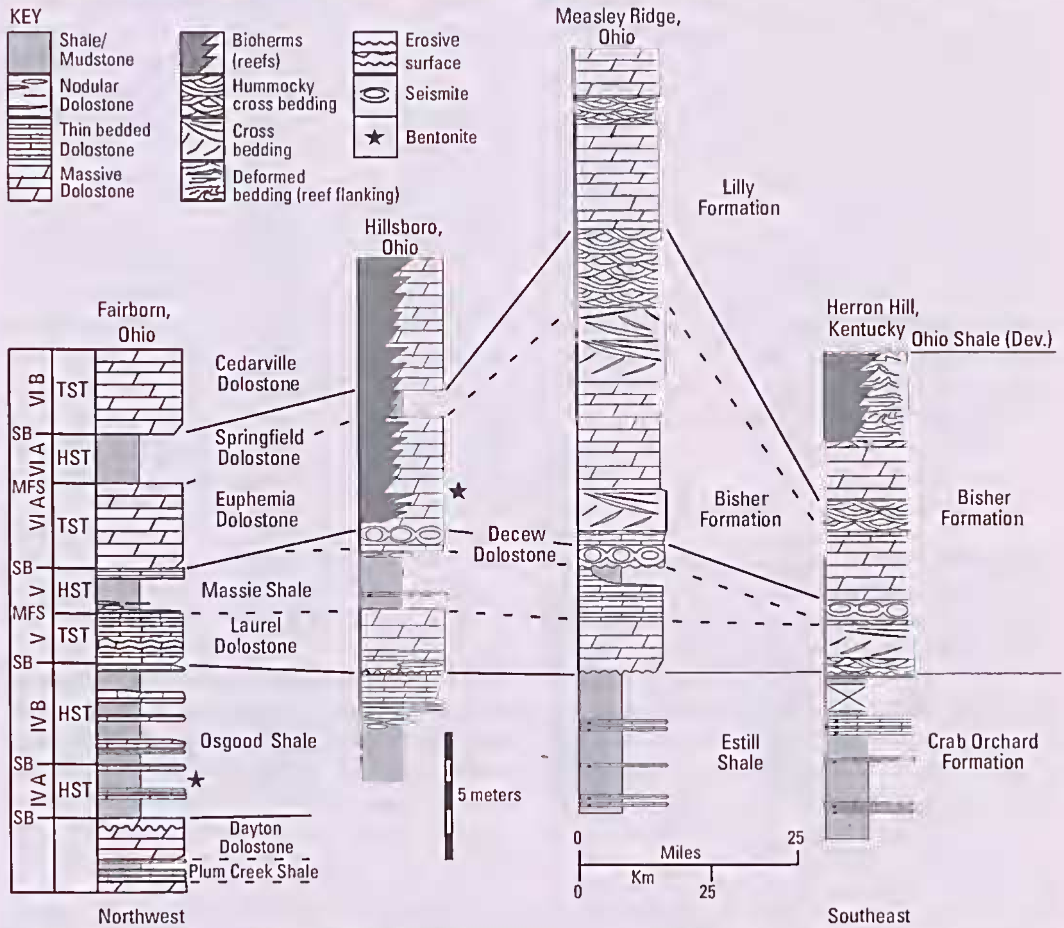

Fig 14. Correlated stratigraphic columns along NW-SE cross-section from Fairborn Quarry just SE of Dayton, Ohio to Herron Hill, Lewis Co., Kentucky. Approximate position of cross section shown in Figure 2. Note comparison of New York-Ontario terminology shown in Fig. 15. Sequence stratigraphic abbreviations as in Fig. 6.

partings, sharply overlain by F) (Cedarville, Lilly Fm.) more massive crinoidal dolostones with local stromatoporoid biostromes and micritic mounds; G) (Lilly, upper Bisher Fm.) local cherty bioturbated dolomicrite; and, finally, H) (Lilly-Peebles transition) shaly dolostone and dolomitic shales, which locally contain bioherms.

The successions in Ohio and Kentucky can be correlated unit for unit with those of the latest Llandovery to Wenlock succession of New York and Ontario, Canada (Figs. 12, 15), as follows: Unit A: Irondequoit Limestone; Unit B) Rochester Shale (partially truncated by erosion to the west in Ontario); Unit C: DeCew Dolostone (a possible widespread seismite); Unit D: lower Gasport Limestone (Gothic Hill Member), crinoidal dolomitic grainstone); Unit E: upper Gasport (Pekin Member), thinly bedded dolostones and bioherms; Unit F: lower Goat Island Formation (Niagara Falls Member), massive crinoidal dolostone; Unit G: middle Goat Island (Ancaster Member) medium to thin bedded cherty dolomicrite; and Unit H: upper Goat Island (Vinemount Member), dolomitic shale and shaly dolostone. In turn, these units represent components (mainly systems tracts) of regionally widespread depositional sequences and subsequences: Unit A: TST of S-V; Unit B: HST of S-V; Unit C: FSST of subsequence S-V (and base of a subsequence); Unit D TST of subsequence S-VIA; Unit E: HST of S-VIA; Units F, G, TST of S-VIB; and Unit H: HST of S-VIB (Fig. 12; see Brett et al. 1990, for definition and discussion of these sequences).

SUMMARY DISCUSSION

Despite a multiplicity of names applied to medial Silurian units in different regions along the eastern to northern flank of the Cincinnati, this area displays the same basic succession of units and indeed, this succession can be matched rather closely with the coeval interval in the Appalachian Basin. The lateral persistence of sequences and their bounding surfaces over much of northeastern to central North America strongly suggests an allocyclic, probably eustatic sea level control on the development of these sequences. However, the local expression of the sequences and their bounding surfaces was modified by far-field tectonics, notably gentle uplift and migration of the Findlay-Algonquin Arch, influenced by lithospheric flexure (Beaumont et al. 1988).

The medial Silurian succession along the eastern flank of the Cincinnati Arch in south-central Ohio, is most comparable to that exposed along the Niagara Escarpment in southern Ontario, Canada and western New York. The similarities of facies and thickness patterns probably reflect the fact that these widely separated areas lay more or less along the same NE-SW trending depositional strike belt.

During Wenlock time the Findlay-Algonquin Arch system was oriented northeast-southwest from near Hamilton, Ontario to southwestern Ohio (Figs. 2, 10). Both the outcrops in southern Ontario and those of south central Ohio represent facies deposited to the southeast of the arch. The Brassfield Dolostone maintains similar thickness and only minor facies change across this region, suggesting that no major positive feature was present in early Llandovery time. However, regional cut out of Sequences S-I to S-III toward the northwest in both New York-southern Ontario and south central Ohio reflects erosional truncation of units along the arch, a probable forebulge that became uplifted during later Llandovery time (Łukasik 1988; Brett et al. 1990). This cut out appears to occur beneath a widespread glauconitic-bioturbated dolostone, the Merritton Dolostone of Ontario and equivalent Dayton Formation in Ohio. Likewise, the thinning and increased carbonate content of the Estill-Osgood interval and sharpening of the contacts from Hillsboro northwest to Fairborn, Ohio reflects a generally positive area in the Findlay-Algonquin Arch (northeast branch of Cincinnati Arch). However, the thickness of the Estill Shale in central Ohio and northern Kentucky more resembles that of the Williamson-Willowvale interval in central New York State, suggesting an abrupt shift in the angle of orientation of the basin axis in late Telychian time (cf. Ettensohn & Brett 1998; Ettensohn 2004). This change in geometry will be discussed more fully in a forthcoming paper.

Not so readily explained is the apparent condensation of sequences S-V and S-VI and the cut out of unit D (Massie-Rochester Shale) to the southeast in northern Kentucky. This suggests the development of a secondary arch to the southeast of the Cincinnati or Findlay arch. In later Silurian and Devonian time this southeastern area becomes the region of maximum truncation. Thus, for example, in areas to the southeast of Vanceburg, Upper Devonian black shales rest successively upon the Bisher, Estill, Brassfield and finally on Upper Ordovician formations. This effect has been attributed to the rise of

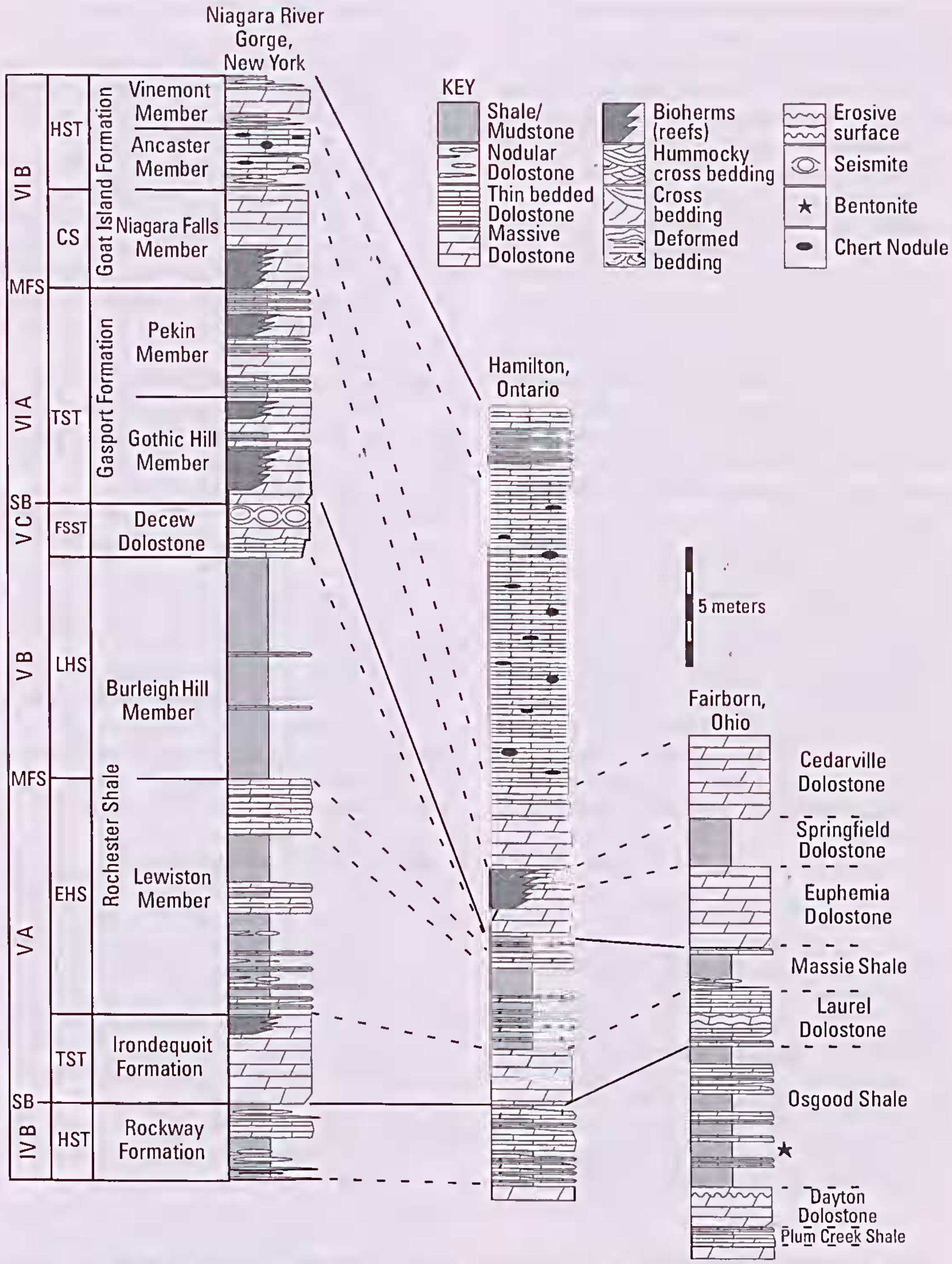

Fig 15. Correlation of late Llandovery to Wenlock stratigraphy of Niagara Gorge, New York, Hamilton, Ontario, and Dayton, Ohio. Sequence stratigraphic abbreviations as in Fig. 6.

the "Cincinnati Arch" during Siluro-Devonian time, although, in fact, it is clear that this positive area was positioned well to the southeast of the present Cincinnati Arch. In any case, it is now apparent that arching in the southeast must have commenced during Wenlock time. The Estill Shale (latest Llandovery) does not appear to have been strongly affected by this arching and indeed thickens to the southeast. Conversely, the Massie-Rochester Shale is largely truncated by the sub-sequence S-VC and/or basal S-VI erosion surfaces in the vicinity of Vanceburg, Kentucky. It is not clear at this time what the exact orientation of the northern Kentucky positive area was, nor how far northward this arch extended. It does not appear in the western New York or Pennsylvania outcrop belts. Further study of subsurface relationships will be needed to clarify these relationships, but these will be aided by the extension of a detailed sequence and event stratigraphic framework.

Finally, both the occurrence of an extremely widespread seismite (DeCew horizon) and newly discovered K-bentonites indicates both seismic and volcanic activity within or at the periphery of the Appalachian foreland basin. This evidence, together with evidence for restructuring and/or migration of arches (forebulges; Beaumont et al. 1988; Ettensohn & Brett 1998; Ettensohn 2004) during the latest Llandovery to Wenlock, indicates renewed active tectonism within the medial Silurian as previously postulated (Goodman & Brett 1994; Ettensohn & Brett 1998).

ACKNOWLEDGMENTS

We thank Warren Huff, Greg Edgecombe, John Talent, and Ruth Mawson for reviewing this paper and suggesting improvements. Mark Kleffner shared unpublished observations on conodont biostratigraphy; Sean Cornell and Pat McLaughlin provided important assistance in the field. Tim Phillips helped in numerous ways in the final preparation of figures. Funding for this research was partially supported by a start-up grant from the University of Cincinnati.

REFERENCES

AIGNER, T., 1985. *Storm Depositional Systems: Dynamic Stratigraphy in Modern and Ancient Shallow Marine Sequences, Lecture Notes in the Earth Sciences 3*. Springer, Berlin, 174 pp.

AUSICH, W.I., 1987. John Bryan State Park: Silurian Stratigraphy. *Geological Society of America DNAG Centennial Field Guide, North Central Section*, p. 419–422.

BEAUMONT, C., QUINLAN, G. & HAMILTON, Z, J., 1988. Orogeny and stratigraphy: Numerical models of the Paleozoic in the eastern interior of North America. *Tectonics* 7: 389–416.

BERRY, W.B.N. & BOUCOT, A.J., 1970. Correlation of the North American Silurian rocks. *Geological Society of America Special Paper* 102: 1–289.

BRENCHLEY, P.J., 2004. End Ordovician glaciation. In *The Great Ordovician Biodiversification Event*. B.D. Webby, F. Paris, M.L. Droser & I.G. Percival, eds, Columbia University Press, New York, 81–83

Brenchley, P.J., Marshall, J.D., Carden, G.A.F., Robertson, D.B.R., Long, D.G.F., Meidi, T., Hints, L. & Anderson, T.F. 1994. Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period. *Geology* 22: 295–298.

BRETT, C.E., 1995. Sequence stratigraphy, biostratigraphy, and taphonomy in shallow marine environments. *Palaios* 10: 597–616.

BRETT, C.E., 1998. Sequence stratigraphy, paleoecology, and evolution: Biotic clues and responses to sea-level fluctuations. *Palaios* 13: 241–262.

BRETT, C.E., BAARLI, B.G., CHOWNS, T., COTTER, E., DRIESE, S., GOODMAN, W. & JOHNSON, M.E., 1998. Early Silurian condensed horizons, ironstones, and sequence stratigraphy in the Appalachian foreland basin. In *Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes*, E. Landing & M.E. Johnson, eds, New York State Museum Bulletin 491: 89–143.

BRETT, C.E., BOUCOT, A.J. & JONES, B., 1993. Absolute depths of Silurian benthic assemblages. *Lethaia* 26: 25–40.

BRETT, C.E., GOODMAN, W.M. & LODUCA, S.T., 1990. Sequences, cycles, and basin dynamics in the Silurian of the Appalachian foreland basin. *Sedimentary Geology* 69: 191–244.

BRETT, C.E., GOODMAN, W.M. & LODUCA, S.T., 1994. Ordovician and Silurian strata in the Genesee Valley area: Sequences, cycles, and facies: *New York State Geological Association Field Trip Guidebook.* 66th Annual Meeting, Rochester, New York 381–442.

BRETT, C. E. & RAY, D.C., 2001. Sequence and event stratigraphy of the Medial Silurian of Eastern North America: comparisons of Appalachian Basin and Cincinnati Arch successions. *Geological Society of America. Abstracts with Programs* 33 (1): A-16.

BRETT, C.E., TEPPER, D.H., GOODMAN, W.M., LODUCA, S.T. & LIN, B.Y., 1995. Revised stratigraphy and correlation of the Niagaran Provincial Series (Medina, Clinton, and Lockport groups) in the type area of western New York. *U.S. Geological Survey Bulletin* 2086: 1–66.

CATUNEANU, O., 2002. Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. *Journal of African Earth Sciences* 35: 1–43.

CROWLEY, D. J., 1973. Middle Silurian patch reefs in the Gasport Member (Lockport Formation), New York. *American Association of Petroleum Geologists Bulletin* 57: 283–300.

COE, A.L. & CHURCH, K.D., 2003. Sequence stratigraphy. In *The Sedimentary Record of Sea-Level Change*, A.L. Coe, ed, Cambridge University Press, 57–98.

DENNISON, J.M. & ETTENSOHN, F.M., eds, 1994. Tectonic and Eustatic Controls on Sedimentary Cycles. *Society for Economic Paleontologists and Mineralogists, Concepts in Sedimentology and Paleontology* 4: 181–201.

DENNISON, J.M., & HEAD, J.M., 1975. Sea-level variations interpreted from the Appalachian Basin Silurian and Devonian. *American Journal of Science* 275: 1089–

EMERY, D. & MYERS, K.J., eds., 1996. *Sequence Stratigraphy.* Blackwell, Oxford, 297pp.

ETTENSOHN, F.R., 1991. Flexural interpretation of relationships between Ordovician tectonism and stratigraphic sequences, central and southern Appalachians, U.S.A. In *Advances in Ordovician Geology*, C.R. Barnes & S.H. Williams, eds, *Geological Survey of Canada Paper* 90-9, 213–224.

ETTENSOHN, F.R., 1992a. *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy. Ohio Division of Geological Survey, Miscellaneous Report* 5, 184 pp.

ETTENSOHN, F.R., 1992b. Basic flexural models. In *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*, F.R. Ettensohn, ed, *Ohio Division of Geological Survey, Miscellaneous Report* 5, 9–12.

ETTENSOHN, F.R., 1992c. General Ordovician paleogeographic and tectonic framework for Kentucky. In *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*, F.R. Ettensohn, ed, *Ohio Division of Geological Survey, Miscellaneous Report* 5, 19–21.

ETTENSOHN, F.R., 1992d. Upper Ordovician-Lower Silurian rocks at Cabin Creek, northeastern Kentucky. In *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*, F.R. Ettensohn, ed, *Ohio Division of Geological Survey, Miscellaneous Report* 5, 159–164.

ETTENSOHN, F.R., 2004. Modeling the nature and development of major Paleozoic clastic wedges in the Appalachian Basin, USA. *Journal of Geodynamics* 37: 657–681.

ETTENSOHN, F.R. & BRETT, C.E., 1998. Tectonic components in Silurian cyclicity: Examples from the Appalachian Basin and global implications. In *Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes* E. Landing, E. & M.E. Johnson, eds, *New York State Museum Bulletin* 491: 145–162.

Ettensohn, F.R. & Brett, C.E., 2002. Stratigraphic evidence from the Appalachian Basin for continuation of the Taconian Orogeny into Silurian time. In *Taconic Convergence: Orogen, Foreland Basin and Craton*, C.E. Mitchell & R. Jacobi, eds, *Physics and Chemistry of the Earth* 27, 279–288.

ETTENSOHN, F.R. & PASHIN, J.C., 1992. A brief structural framework of Kentucky. In *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*, F.R. Ettensohn, ed, *Ohio Division of Geological Survey, Miscellaneous Report* 5, 6–9.

FOERSTE, A.F., 1906. The Silurian, Devonian, and Irvine formations in east-central Kentucky. *Kentucky Geological Survey Bulletin* 7: 369 pp.

FOERSTE, A.F., 1935. Correlation of Silurian formations in southwestern Ohio and southeastern Indian, Kentucky, and western Tennessee. *Bulletin, Scientific Laboratory, Denison University* 30: 119–205.

Frest, T.J., Brett, C.E. & Witzke, B., 1999. Caradocian to Gedinnian echinoderm associations of central and eastern North America. In: *Palaeocommunity Analysis: A Silurian-Lower Devonian Example*, A.J. Boucot & J.D. Lawson, eds, Cambridge University Press, 638–783.

Fuentes, S., Over, D.J. & Brett, C. E., 2001. Conodont biostratigraphy of "Olentangy" Shale in northeastern Kentucky. In: Sequence, Cycle, and Event Stratigraphy of Upper Ordovician and Silurian Strata of the Cincinnati Arch Region. T.J. Algeo & C.E. Brett, eds, *Kentucky Geological Survey Guidebook* 1, Kentucky Geological Survey, Lexington, Kentucky, p. 136–140.

Goodman, W.M. & Brett, C.E., 1994. Tectonic vs. eustatic controls on the stratigraphic architecture of the Silurian, northern Appalachian Basin. In *Tectonic and Eustatic Controls on Sedimentary Cycles: Society of Economic Paleontologists and Mineralogists, Concepts in Sedimentology and Paleontology*, J.M. Dennison & F.M. Ettensohn, eds, 4: 147–169.

Gordon, L.A. & Ettensohn, F.R., 1984. Stratigraphy, depositional environments, and regional dolomitization of the Brassfield Formation (Llandoverian) in east-central Kentucky. *Southeastern Geology* 25: 101–115.

Grahn, Y. & Caputo, M., 1992. Early Silurian glaciation in Brazil. *Palaeogeography, Palaeoclimatology, Palaeoecology* 99: 9–15.

Haq, B.U., Hardenbol, J. & Vail, P.R., 1987. Chronology of fluctuating sea-levels since the Triassic. *Science* 235: 1153–1165.

Holland, S.M., 1993. Sequence stratigraphy of a carbonate-clastic ramp: The Cincinnatian Series (Upper Ordovician) in its type area. *Geological Society of America Bulletin* 105: 306–322.

Holland, S. M., 1998. Sequence stratigraphy of the Cincinnatian Series (Upper Ordovician, Cincinnati, Ohio, region). In *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*, R.A. Davis & R.J. Cuffey, eds, *Ohio Division of Geological Survey, Guidebook* No. 13, 135–151.

Huddle, J.W., 1967. Silurian conodonts from Kentucky: *U.S. Geological Survey Professional Paper, Geological Survey Research*, 1967, 377 pp.

Huff, W.D., Morgan, D.J. & Rundle, C.C., 1997. Silurian K-bentonites of the Welsh borderlands: Geochemistry, mineralogy and K-Ar ages of illitization. *BGS Technical Report WG/96/45 Mineralogy and Petrology Series* 25pp.

Johnson, M.E., 1996. Stable cratonic sequences and a standard for Silurian eustasy. In *Paleozoic Sequence Stratigraphy: Views from the North American Craton*, B.J. Witzke, G.A. Ludvigson & J.E. Day, eds, *Geological Society of America Special Paper* 306, 203–211.

Johnson, M.E., Rong, J.Y. & Kershaw, S., 1998. Calibrating Silurian eustasy by erosion and burial of coastal paleotopography. In *Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes*, E. Landing & M.E. Johnson, eds, *New York State Museum Bulletin* 491: 3–13.

Kaljo, D., Johnson, M.E., Kiipli, T. & Martma, T., 1998. Correlation of carbon isotope events and environmental cyclicity in the East-Baltic Silurian. In *Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes*, E. Landing & M.E. Johnson, eds, *New York State Museum Bulletin* 491, p. 297–312.

Kidwell, S.M., 1991. The stratigraphy of shell concentrations. In *Taphonomy: Releasing the Data Locked in the Fossil Record*, P.A. Allison & D.E.G. Briggs, eds, Plenum, New York, 211–290.

Kleffner, M.A., 1987. Conodonts of the Estill Shale and Bisher Formation (Silurian, southern Ohio): Biostratigraphy and distribution. *Ohio Journal of Science* 87: 78–89.

Kleffner, M.A., 1989. A conodont-based Silurian chronostratigraphy. *Geological Society of America Bulletin* 101: 904–912.

Kleffner, M.A., 1990. Wenlockian (Silurian) conodont biostratigraphy, depositional environments, and depositional history along the eastern flank of the Cincinnati Arch in southern Ohio. *Journal of Paleontology* 64: 319–328.

Kleffner, M.A. & Ausich, W.I., 1988. Lower and Middle Silurian of the Eastern Flank of the

Cincinnati Arch and the Appalachian Basin Margin, Ohio. *Field Trip 1. Society of Economic Paleontologists and Mineralogists*, Fifth Midyear Meeting, Columbus, Ohio, 25.

LEBOLD, J.G., 2000. Quantitative analysis of epizoans on Silurian stromatoporoids within the Brassfield Formation. *Journal of Paleontology* 74: 394–403.

LIN, B.Y. & BRETT, C.E., 1987. Stratigraphy and disconformable contacts of the Williamson-Willowvale interval: revised correlations of the Late Llandoverian (Silurian) in New York State. *Northeastern Geology* 10: 241–253.

LODUCA, S.T. & BRETT, C. E., 1994. Revised stratigraphic and facies relationships of the lower part of the Clinton group (Middle Llandoverian) of western New York State. In *Studies in Stratigraphy and Paleontology in Honor of Donald W. Fisher*, E. Landing, ed, *New York State Museum Bulletin* 48(1): 161–182.

LUKASIK, D.M., 1988. Lithostratigraphy of Silurian rocks in southern Ohio and adjacent Kentucky. *Ph.D. dissertation (unpubl.)*, University of Cincinnati, 313 pp.

MASON, C.E., LIERMAN, R.T., ETTENSOHN, F.R. & PASHIN, J.C., 1992a. Tempestite lithofacies of the Bisher Dolostone and Crab Orchard Shale (Middle Silurian) along Kentucky State highway 546, northeastern Kentucky, Charters section. In *Changing Interpretations of Kentucky Geology: Layer-Cake, Facies, Flexure and Eustasy*, F.R. Ettensohn, ed, *Ohio Division of Geological Survey, Miscellaneous Report* 5, 153–155.

MASON, C.E., LIERMAN, R.T., ETTENSOHN, F.R., & PASHIN, J.C., 1992b. Sandbelt lithofacies of the Bisher Dolostone, the Crab Orchard Shale, the Upper Olentangy Shale, and the Huron Member of the Ohio Shale in northeastern Kentucky. In *Changing Interpretations of Kentucky Geology: Layer-Cake, Facies, Flexure and Eustasy*, F.R. Ettensohn, ed, *Ohio Division of Geological Survey, Miscellaneous Report* 5, 156–158.

MCLAUGHLIN, P.I. & BRETT, C.E., 2004. Eustatic and tectonic control on the distribution of marine seismites: examples from the Upper Ordovician of Kentucky, USA. *Sedimentary Geology* 168: 165–192.

MYERS, K.J. & MILTON, N.J., 1996. Concepts and principles. In *Sequence Stratigraphy*, D. Emery & K.J. Myers, eds, Oxford, Blackwell, 11–44

POPE, M.C., READ, J.F., BAMBACH, R. & HOFFMAN, H.J., 1997. Late Middle to Late Ordovician seismites of Kentucky, southwest Ohio and Virginia: Sedimentary recorders of earthquakes in the Appalachian Basin. *Geological Society of America Bulletin* 109: 489–503.

POTTER, P.E., 1996. Exploring the Geology of the Cincinnati/Northern Kentucky Region. *Kentucky Geological Survey, Special Publication* 22, Series XI, 115 pp.

POTTER, P.E., AUSICH, W.I., KLEE, J., KRISSEK, L.A., MASON, C. E., SCHUMACHER, G.A., WILSON, T.R. & WRIGHT, E.M., 1991. Geology of the Alexandria-Ashland Highway (Kentucky Highway 546), Maysville to Garrison. *Lexington, Kentucky Geological Survey Joint Field Conference, Geological Society of Kentucky and Ohio Geological Society*, 64pp.

PRATT, B.R. & MIALL, A. D., 1993. Anatomy of a bioclastic grainstone megashoal (Middle Silurian, southern Ontario) revealed by ground-penetrating radar. *Geology* 21: 223–226.

RAY, D.C. & BRETT, C.E., 2001. Sequence and event stratigraphy of the type Wenlock (Silurian): Midland Platform England: Comparison with eastern Laurentia. *Geological Society of America Abstracts with Programs* 33 (1): A-16.

REXROAD, C.B., 1970. An outline of Silurian conodont zones in the Illinois Basin and the Cincinnati Arch area. In *Correlation of the North American Silurian rocks*, W.B.N. Berry & A.J. Boucot, eds, *Geological Society of America Special Paper* 102, 91–94.

REXROAD, C.B. & RICKARD, L.V., 1965. Zonal conodonts from the Silurian strata of the Niagara Gorge. *Journal of Paleontology* 39: 1217–1220.

SCHNEIDER, K.A. & AUSICH, W.I., 2002. Paleoecology of framebuilders in Early Silurian reefs (Brassfield Formation, Southwestern Ohio): *Palaios* 17: 237–248.

SCOTESE, C.R., 1990. Atlas of Phanerozoic Plate Tectonic Reconstructions: International Lithophase Program (IUU-IUGS), *Paleomap Project Technical Report* 10-90-1.

SLOSS, L.L., 1963. Sequences in the cratonic interior of North America. *Geological Society of America Bulletin* 74: 93–114.

SMOSNA, R. & PATCHEN, D., 1978. Silurian evolution of the central Appalachian Basin. *American Association of Petroleum Geologists, Bulletin* 62: 2308–2328.

STOTT, C.A. & VON BITTER, P. M., 1999. Lithofacies and age variation in the Fossil Hill Formation (Lower Silurian), southern Georgian Bay region, Ontario. *Canadian Journal of Earth Sciences* 36: 1743–1762.

TELFORD, P.G., 1978. Silurian stratigraphy of the Niagara Escarpment, Niagara Falls to the Bruce Peninsula: *Geological Association of Canada, Toronto '78 Field Trips Guidebook*, p. 28–42

VAIL, P.R., MITCHUM, R.M., JR. & THOMPSON, S., III, 1977. Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes in sea level. In *Seismic Stratigraphy Applications to Hydrocarbon Exploration*, C.E. Payton, ed, *American Association of Petroleum Geologists, Memoir* 26, 83–97.

VAIL, P.R., AUDEMARD, F., BOWMAN, S.A., EISNER, P.N. & PÉRÈZ-CRUZ, C., 1991. The stratigraphic signatures of tectonics, eustasy and sedimentation: An overview. In *Cycles and Events in Stratigraphy*, G. Einsele, W. Ricken & A. Seilacher, eds, Springer, New York, 617–659.

VAN WAGONER, J.C., POSAMENTIER, H.W., MITCHUM, R.M., III, VAIL, P.R., SARG, J.F., LOUTIT, T.S. & HARDENBOL, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In *Sea-Level Changes: An Integrated Approach*, C.K. Wilgus, B.S. Hastings, C.G. Kendall, H.W. Posamentier, C.A. Ross & J.C. Van Wagoner, eds, *Society of Economic Paleontologists and Mineralogists, Special Publication* 42, 39–45.

WILGUS, C.K., HASTINGS, B.S., KENDALL, C.G., POSAMENTIER, H.W., ROSS, C.A. & VAN WAGONER, J.C., eds, 1988. Sea-Level Changes: An Integrated Approach. *Society of Economic Paleontologists and Mineralogists, Special Publication* 42. 407 pp.

WITZKE, B.J., LUDVIGSON, G.A. & DAY, J.E., 1996. Introduction: Paleozoic applications of sequence stratigraphy. In *Paleozoic Sequence Stratigraphy: Views from the North American Craton*, B.J. Witzke, G.A. Ludvigson & J.E. Day, eds, *Geological Society of America Special Paper*, 1–6.